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Cost Analysis for a Hybrid Advanced Metering Infrastructure in Korea

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Abstract: Advanced metering infrastructure (AMI) refers to the electricity service infrastructure between electricity consumers and suppliers and is technically essential for the realization of a smart grid environment. To implement AMI, various communications technologies are being used based on the application environment according to the utility. However, using a single communications method can give rise to attenuation in the downtown underground distribution line section or cause higher supply costs due to decreased density in the range from farming to fishing areas. A hybrid AMI is one solution to this problem. According to an economic analysis of previous AMI deployment, the cost to install a communications network accounts on average for 45% of the total cost. Since the installation cost of a communications network is influenced by the density of the installation environment, a hybrid AMI, which allows the configuration of a flexible network using both wired and wireless communications, can be a good alternative, both technically and financially. This study conducted a simulation based on density of the installation environment and configuration of the communications network to analyze the economic effect of installing a hybrid AMI communications network. It assumed that a hybrid AMI was deployed in an overhead distribution line in a low-density area. The simulation outcomes were compared and analyzed against the power line communication (PLC)-only AMI method. The results showed that the hybrid AMI method had a 10% communications network cost reduction effect compared to the PLC-only AMI method. In addition, the analysis indicated that there was a maximum 19% cost reduction effect in communications network installation depending on the method of network installation, suggesting that the hybrid AMI was economically more effective than the PLC-only AMI method.

Keywords: advanced metering infrastructure (AMI); hybrid AMI; cost analysis; system dynamics

1. Introduction

Advanced metering infrastructure (AMI) is the electricity service infrastructure between electricity consumers and suppliers that uses two-way communications to read energy use, collect energy-use information, apply rates, and enable additional services [1–4]. The technology is essential for the realization of a smart grid environment. Currently, the provision of AMI is spreading rapidly worldwide. In Europe, by the middle of 2012, about 90 smart-metering pilot projects and country-specific rollouts were conducted. According to the European Commission, Member States aimed to supply 200 million smart meters by 2020 [5]. This indicates that more than 70% of users will be included in Smart Grid technology through the use of smart meters [6]. The United States has installed 65 million smart meters covering more than 50% of households by the end of 2015 and expects to install 90 million smart meters by 2020 [7]. As part of the national plan, China is promoting the spread of smart meters, and 150 million smart meters have been introduced by 2015 and are expected to grow steadily at an average annual rate of 8% by 2020 [5,8]. Japan has set a goal of monitoring 80% of its electricity consumption nationwide and is expected to install a smart meter in about 80 million households by 2024 [5]. According to industry reports in India, it is estimated that by 2021, 130 million smart meters with both PLC and wireless technologies will be installed [5]. In Korea, the utility company (KEPCO) is aiming for a 100% installation of smart meters in the country's entire 21.94 million low-voltage customers by 2020 [9,10].

To implement AMI, various communications technologies are being used based on application environments according to the utility's preference. AMI communication can be classified into the wire and wireless communication [11]. One of the popularly used wire communication methods is power line communication (PLC) [12], which has the advantages of low investment cost by using existing power line infrastructure [12–14]. PLC is divided into broadband PLC, using frequencies up to 30 MHz, and narrowband PLC using frequencies up to 500 kHz [5]. However, this has a disadvantage in that the bandwidth is limited and the attenuation increases as the transmission distance increases [15,16]. Wireless communication methods include WiFi-Mesh (IEEE 802.11s), ZigBee (IEEE 802.15.4), smart utility network (SUN: IEEE 802.15.4g), and TV White Space (IEEE 802.22b) [12,13,17]. The wireless communication methods have the advantages of high data throughput, fast data rate and flexible network configuration [12,15]. However, there is a disadvantage that interference caused by other wireless devices, the terrain and objects can occur [15]. This AMI communication technology is applied considering the regional characteristics and policies of each country [18]. In Europe, PLC is used as a typical communication technology, and especially narrowband PLC is widely used [19]. RF is preferred in the United States, and Pacific Gas & Electric in California and Florida Power and Light Company use RF Mesh [5,19]. Canada uses RF Mesh and ZigBee, China prefers PLC, and India uses PLC and wireless technology [19].

Utility companies tend to select a single communication technology because of the resulting cost reduction and ease of maintenance. However, the choice of a single technology can lead to unexpected adverse effects in some areas. For example, when using a power line communication (PLC) technology, the installation cost can increase in farming and fishing areas due to the decrease of customer density between spans. On the other hand, the communications performance can be degraded in downtown underground distribution line sections. In the underground distribution line sections, signal leakage to the surrounding material around the conduit through the distribution line is high, resulting in a high level of signal attenuation [20,21]. Especially, there are some study results suggesting that the communication performance is significantly lower than that of the high-voltage line, which has excellent shielding characteristics in the case of low-voltage lines [22–27].

A hybrid AMI using multiple communication technologies depending on the situations is one of the solutions to solve the problems [28]. Improving on the existing method, which limits communications between the smart meter and the data concentration unit (DCU) to one technology, a hybrid AMI is a system that is configured with either a mixed method using multiple communications technologies as supplements or a combined method using multiple communications technologies for dualization.

For successful implementation of a hybrid AMI, technical issues should be resolved and the hybrid AMI should be cost effective and economically feasible. Accordingly, a cost analysis that takes account of all the factors causing cost fluctuation must first be conducted during the initial stages of deploying the hybrid AMI.

According to analyses performed on the economics of existing AMI technologies, the communications network accounts for an average of 45% of the total installation cost [29]. Since the equipment comprising the communications network entails operation and maintenance (O&M) costs, a communications network installation plan suited to the installation environment needs to be devised during the initial stages of the undertaking from a long-term perspective. Since the installation cost of a communications network is influenced by the density of the installation environment, a hybrid AMI, which allows the configuration of a flexible network using both wired and wireless communications, can be a good alternative, both technically and financially [29].

This study conducted a cost analysis based on the density of the installation environment and the configuration of the communications network to evaluate the economic effects of installing a hybrid AMI communications network. To this end, the study deduced major cost factors of the hybrid AMI and built a cost model taking account of consumer density and wire methodology. Korea had determined to use a broadband PLC technology based on IEC 12139-1 at the initial stage of AMI deployment. Recently, adopting a hybrid AMI method has been studied to improve economics and efficiency combining wireless technology. Therefore, a PLC-only AMI method is considered as the reference model, and a hybrid AMI method with PLC and wireless communication are compared in this work. Here, ZigBee and SUN are implicitly considered as the wireless technology. In this study, the density of the installation environment was simplified into downtown and non-downtown areas, and it was assumed that hybrid AMI is deployed in the overhead distribution line in a non-downtown area, which is a low-density region. A simulation was run based on a power line communication (PLC)-only AMI method installation and a hybrid AMI method installation under the AMI deployment plan considering the situation of Korea and the proposed cost model. Based on the simulation results, a comparison was made of major cost factors and a sensitivity analysis was performed, after which the economic effects of the hybrid AMI were presented accordingly.

2. Hybrid Advanced Metering Infrastructure Cost Model

2.1. Hybrid AMI Concept

The AMI system primarily communicates through smart meters usually installed in consumer connections, and it has a hierarchical structure composed of a DCU, which collects information, and a meter data management system (MDMS), which oversees the overall consolidation and management of gathered information [30–32]. Improving on the existing method of limiting communications between the smart meter and the DCU to one technology, a hybrid AMI environment is a system comprised of either a mixed method that uses multiple communications in a complementary fashion or a combined method that dualizes multiple communications, depending on the environment. The communications technology between the smart meter and the DCU can be applied with various wired and wireless communications, including PLC, WiFi, ZigBee, TVWS, and SUN, and the infrastructure is structured in a way that allows changes to the communications method via repeaters and enables cell expansion. Figure 1 illustrates the structure of the hybrid AMI.

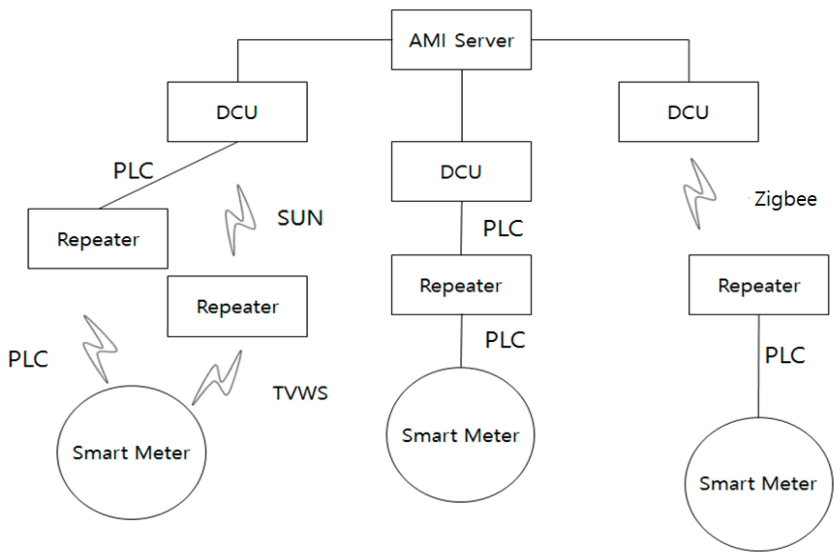

Figure 1. Hybrid Advanced Metering Infrastructure Structure.

2.2. Categorization of Hybrid AMI Installation Environment

Unlike the existing communications method, it is possible to select a communications method based on the configuration of the communications network in a hybrid AMI environment. Because the configuration of a communications network is influenced by the residential environment, such as density and distance, it is necessary to categorize the installation environments to perform an effective cost analysis. According to an economic analysis on existing AMI, the average cost per consumer can vary by more than twice the value depending on consumer density [29]. In North America, Southern California Edison (51,000 m^2) covered more than 20 times the area that Con Edison covered in a low-voltage consumer service area (2200 m^2), leading to higher network installation and maintenance costs [29]. These results indicate that the AMI deployment cost is influenced by consumer density. This study accordingly categorized installation environments into high-density regions and low-density regions.

2.3. Hybrid AMI Cost Model

According to the guideline for conventional cost analysis, the analysis consists of three steps: the definition of the scenario, the main parameter settings, and the analysis, then additional sensitivity analysis can be performed [33–35]. In this study, the cost analysis model structure can be divided largely into a hybrid AMI deployment environment setup scenario and a cost setup. The hybrid AMI deployment environment setup was categorized into an overhead distribution line section and an underground distribution line section in order to apply wired and wireless communications methods according to the type of distribution line based on the area's consumer density. Communications networks in a hybrid AMI environment are made up of a single cell containing a DCU with a communications modem and a repeater. The major cost factors for the communications network installation can be separated into costs required for equipment purchase and installation as well as the subsequent O&M cost. The main factors of each cost factor include DCU, communications modem, smart meter, and repeater. In this study, to improve the accuracy of the cost model, a formulation was made considering the type of smart meters, the architecture of communication modem connectivity, the cost change according to the number of deployment, the customer density of regions, the type of distribution lines, etc. The detailed cost model is as follows.

2.3.1. DCU

The DCU installation cost can be calculated by applying the unit price of equipment and installation based on the DCU deployment quantity, as shown in Equation (1). The average DCU quantity according to installation region, or $DCUQ_{y,r,i}$, is classified into single installation methods and hybrid installation methods, and it is calculated by taking account of the average quantity of communication modems accepted per area, as observed in Equation (2). The DCU entails operational costs for using the backbone network as well as maintenance costs. The O&M cost is applied from the following year of the installation, and it can be defined as Equation (3):

$$DCUC_y^{DP} = (DCUP_y^{HW} + DCUP_y^{InsT}) \cdot \sum_{r \in R, i \in I} DCUQ_{y,r,i}, \quad (1)$$

$$DCUQ_{y,r,i} = SMQ_{y,r,i} / DCU_{y,r,i}^{Cover}, \quad (2)$$

$$DCC_y^{O\&M} = \sum_{\tau=0}^{y-1} \sum_{r \in R, i \in I} (DCUP_\tau^O + DCUP_\tau^M) DCUQ_{\tau,r,i}, \quad (3)$$

2.3.2. Smart Meter

A smart meter is a one-per consumer piece of equipment, and they have various unit prices based on any additional functions. The total deployment cost of smart meters per year can be defined using the formulas below based on the AMI deployment quantity, the deployment ratio per smart meter type, and the unit price for equipment and installation per type. Since smart meters are replaced when they break down or reach the end of their life cycle, no maintenance costs are incurred [36]:

$$SMC_y^{DP} = (SMP_y^{HW} + SMP_y^{InsT}) \cdot \sum_{i \in I, r \in R} SMQ_{y,i}, \tag{4}$$

$$SMQ_{y,i} = \sum_{g \in G} AMID_{y,r,g} \cdot SMR_{y,r,g,i}, \tag{5}$$

2.3.3. Communications Modem

Communications modems need to be applied with the characteristics of the overhead distribution line or the underground distribution line due to the nature of their communications method with the DCU or the repeater, and the smart meter and the communications modem need to be applicable by 1:1 or 1:N, depending on the consumer environment. The cost of installing a communications modem can be calculated by the average quantity of communications modems by type (wired or wireless) in the deployment area and the equipment cost, as defined in Equation (6):

$$CMC_y^{DP} = \sum_{r \in R, j \in J} CMQ_{y,r,j} \cdot (CMP_{y,j}^{HW} + CMP_{y,j}^{InsT}), \tag{6}$$

The average quantity of communications modems within the $CMQ_{y,r,j}$ installation region can be estimated by the total quantity of smart meters, the ratio of the overhead distribution line to the underground distribution line, the proportion of the wired communications method to the wireless communications method, and the average quantity ratio of smart meters per communications modem, which is defined in the following equation:

$$\begin{gathered} CMQ_{y,r,j} = \sum_{k \in K, i \in I} SMQ_{y,r,i} \cdot OUR_{y,r,k} \cdot CMR_{y,r,i,j}^{Type} / CS_{y,r,i,j}^{Cover}, \\ where, \begin{cases} if\ (k = 0),\ CMR_{y,r,0,0} = 1,\ else = 0 \\ if\ (k = 1),\ otherwise \end{cases} \end{gathered} \tag{7}$$

It was assumed that the underground distribution line (k = 0) in this model was installed with only wired communications, considering the efficiency issues of the wireless communications method. Communications modems entail maintenance costs, which can be defined as the following Equation (8):

$$CMC_y^{M} = \sum_{\tau=0}^{y-1} \sum_{r \in R, i \in I} CMQ_{\tau,r,j} \cdot CMP_{\tau,j}^{M}, \tag{8}$$

2.3.4. Repeater

Repeaters are used for combining communications methods after communications attenuate due to the expansion of cell configuration following the application of a hybrid form of communications method. The installation cost of repeaters by year can be defined as Equation (9). Here, $RPQ_{y,r,i}$ refers to the average quantity of repeaters per area, and it can be calculated by multiplying the average quantity of repeaters per DCU in each area, or $RPR_{y,r,i}$, as shown in Equation (10). Repeaters entail yearly maintenance cost, which can be defined as Equation (11) below:

$$RPC_y^{DP} = (RPP_y^{HW} + RPP_y^{InsT}) \cdot \sum_{r \in R, i \notin 0} RPQ_{y,r,i}, \tag{9}$$

$$RPQ_{y,r,i} = DCUQ_{y,r,i} \cdot RPR_{y,r,i}, \tag{10}$$

$$RPC_y^{M} = \sum_{\tau=0}^{y-1} \sum_{r \in R, i \notin 0} RPQ_{\tau,r,i} \cdot RPP_{\tau}^{M}, \tag{11}$$

2.3.5. Hybrid AMI Cost Analysis Model

Once the installation environment is set up based on the density of the AMI deployment location as well as through the setup of the overhead distribution line and the underground distribution line, the deployment plan should be implemented based on the previously set installation environment. This is where the quantity of smart meters for the installation location is determined and the smart meter type is set up taking account of consumer characteristics. In order to install an average communications network per region, the configuration relations should be set up between the DCU, the smart meter, and the repeater, taking account of the area and the wire configuration type that was previously set. Based on the formerly set installation environment, the total cost can be estimated by applying the unit price of equipment, installation, and O&M. Figure 2 shows the hybrid AMI cost analysis model.

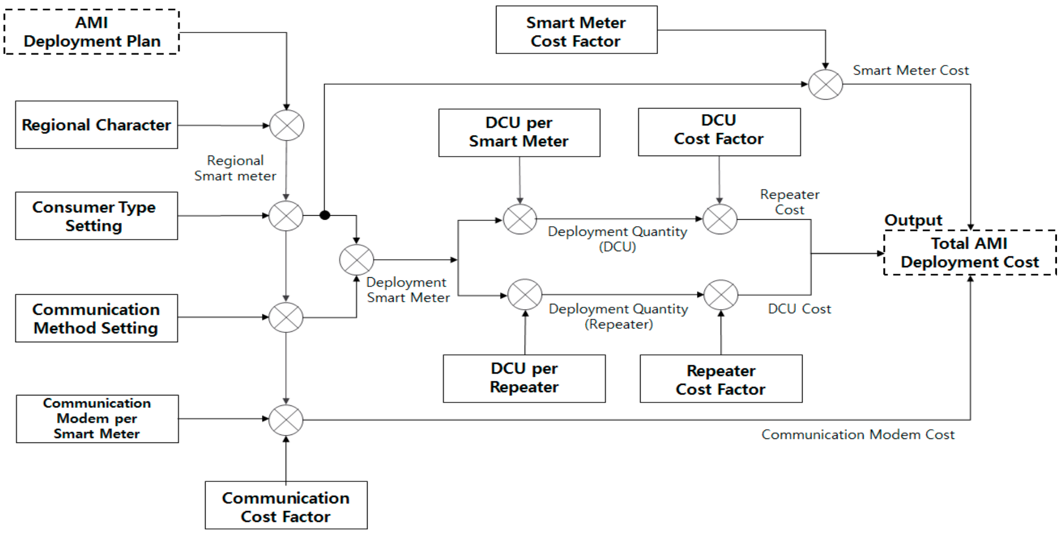

Figure 2. Hybrid AMI System Model.

Each cost factor of the AMI cost model influences each another depending on the deployment plan. This study used a system dynamics-based tool, Powersim, to realize the model in order to perform an effective cost analysis. Figure 3 is an illustration of the system dynamics model structure of the AMI cost model.

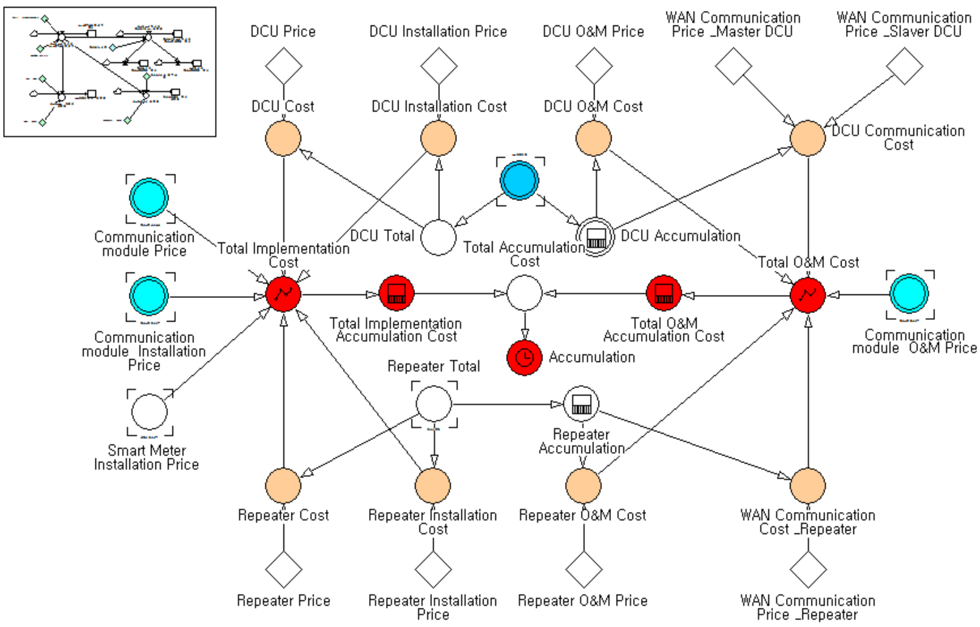

Figure 3. System Dynamics Modeling for Hybrid AMI.

3. Simulation and Discussion

3.1. Simulation Scenario

This study assumed that the hybrid AMI was deployed in the overhead distribution line within a low-density region. According to the simulation scenario setup, the classification system in reference [37] was referred to for the AMI installation environment: the high-density region and the low-density region were applied by simplifying them into the downtown area and the non-downtown area, respectively. The proportion of the downtown area to the non-downtown area was set as 6:4, as referred to in references [37,38], and the wire type was applied with the late 2012 wire ratio of 8.5:1.5 between the overhead distribution line and the underground distribution line [38]. This study chose to deploy the hybrid AMI in the overhead distribution line within a non-downtown area, and assumed based on the setup results in Section 2 that the hybrid AMI accounted for 34% of the total deployment goal. The installation plan reflects the AMI deployment plan devised by existing Korean electric companies; a 15-year cost analysis scenario was built assuming there would be approximately 1.2% new targets for installation once the deployment was completed. The following Table 1 presents the AMI deployment scenario.

Table 1. AMI Deployment Scenario.

AMI Deployment Scenario		
Year	**Plan (10K)**	**Accumulation (10K)**
2016	200.0	200.0
2017	230.0	430.0
2018	250.0	680.0
2019	257.5	937.5
2020	250.0	1187.5
2021	250.0	1437.5
2022	330.0	1767.5
2023	364.0	2131.5

In downtown areas, the PLC was set up by applying the existing AMI deployment method. The quantity of smart meters per DCU of the PLC was applied with the average referred to in reference [36], and the setup ensured no repeater was applied. In non-downtown areas, the setup involved both the PLC and the wireless in a hybrid form, in the ratio of 5:5. Considering that the maximum quantity of smart meters the hybrid AMI aims to accommodate is 500, it was assumed in this study that the quantity of smart meters per DCU was 250 on average [39]. Another assumption was that 2.5 repeaters on average were used per DCU. As for the unit price of equipment for the communications modem and the DCU, changes in unit price per deployment quantity were referred to in reference [37], and a cost curve with the target unit price of 1PU (Per Unit) was applied, as shown in Figure 4. Furthermore, the target unit price for 2 million households in reference [36] was used for installation and O&M costs.

3.2. Simulation Results and Discussion

3.2.1. Total Cost

The total AMI deployment cost amounted to 3116 billion KRW for PLC-only AMI and 2942 billion KRW for hybrid AMI. The analysis shows that as of 2030, the hybrid AMI would have a cost reduction effect of 5.6% or 174 billion KRW compared to the PLC-only AMI. Table 2 presents the total deployment cost result by deployment type.

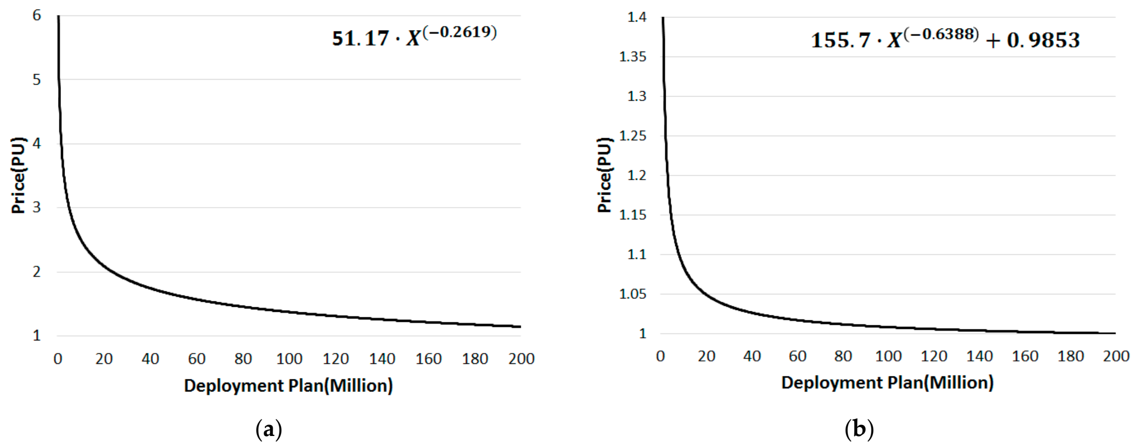

Figure 4. Communications Modem and DCU Cost Curve: (**a**) Communications Modem Cost Curve; (**b**) DCU Cost Curve.

Table 2. Total Deployment Cost Result by Deployment Type (Billion KRW).

Year	AMI Deployment Scenario Cost		
	PLC-Only	Hybrid	Reduction Ratio (%)
2016	206.2	198.2	3.9
2017	446.6	427.6	4.3
2018	713.4	681.1	4.5
2019	994.8	947.8	4.7
2020	1277.6	1215.3	4.9
2021	1568.8	1490.3	5.0
2022	1947.5	1847.5	5.1
2023	2370.8	2246.5	5.2
2024	2474.3	2343.1	5.3
2025	2578.8	2440.6	5.4
2026	2684.2	2539.1	5.4
2027	2790.6	2638.4	5.5
2028	2898.0	2738.6	5.5
2029	3006.3	2839.6	5.5
2030	3115.5	2941.6	5.6

The analysis indicated that the deployment cost item incurring the highest cost is the smart meter installation cost; it constituted about 45–48% of the total cost. Table 3 displays the results of the comparison between the total cost and smart meter cost.

Examining the cost result from the perspective of a communications network that excludes smart meters from the total deployment cost, the hybrid AMI showed a 173 billion KRW cost reduction compared to the PLC-only AMI as of 2030, which equals a 10.2% cost reduction effect. Table 4 below shows a comparison of the cost results of communications networks per deployment type, and Figure 5 presents the cost summary results per deployment type.

Table 3. Comparison Results of Total Deployment Cost and Smart Meter Cost (Billion KRW).

Year	Deployment Cost (Smart Meter)		
	Smart Meter	Cost Percentage	
		PLC-Only (%)	Hybrid (%)
2016	122.0	59.2	61.6
2017	262.3	58.7	61.3
2018	414.8	58.1	60.9
2019	571.6	57.5	60.3
2020	724.1	56.7	59.6
2021	876.6	55.9	58.8
2022	1077.9	55.3	58.3
2023	1299.9	54.8	57.9
2024	1316.1	53.2	56.2
2025	1332.3	51.7	54.6
2026	1348.6	50.2	53.1
2027	1364.8	48.9	51.7
2028	1381.0	47.7	50.4
2029	1397.2	46.5	49.2
2030	1413.4	45.4	48.0

Table 4. Communications Network Cost per Deployment Type (Billion KRW).

Year	Communications Network Deployment Cost		
	PLC-Only	Hybrid	Reduction Cost Ratio (%)
2016	84.2	76.2	9.5
2017	184.3	165.3	10.3
2018	298.6	266.3	10.8
2019	423.3	376.2	11.1
2020	553.6	491.2	11.3
2021	692.2	613.7	11.3
2022	869.6	769.7	11.5
2023	1070.9	946.6	11.6
2024	1158.2	1027.0	11.3
2025	1246.4	1108.3	11.1
2026	1335.7	1190.5	10.9
2027	1425.8	1273.6	10.7
2028	1517.0	1357.6	10.5
2029	1609.1	1442.4	10.4
2030	1702.1	1528.2	10.2

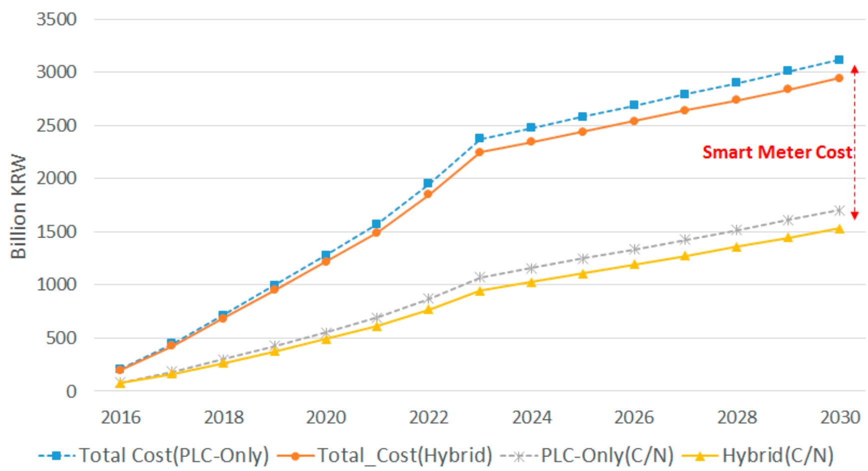

Figure 5. Costs by Deployment Type and Installation Item (C/N: Communication Networks).

3.2.2. Installation and O&M Cost

Examining installation and O&M costs, Table 5 displays the installation costs as of 2030 for PLC-only AMI (900.2 billion KRW) and hybrid AMI (782.6 billion KRW), indicating a 13.1% cost decrease in hybrid AMI compared with PLC-only AMI.

Table 5. Comparison of Installation Cost Result per Deployment Method (Billion KRW).

Year	Installation Cost			
	PLC-Only	Hybrid	Reduction	
			Cost	Ratio (%)
2016	84.2	76.2	8.0	9.5
2017	177.1	158.5	18.6	10.5
2018	275.7	245.0	30.7	11.1
2019	375.7	332.1	43.6	11.6
2020	472.1	415.5	56.6	12.0
2021	567.7	497.9	69.8	12.3
2022	692.9	605.4	87.5	12.6
2023	830.1	722.8	107.3	12.9
2024	840.2	731.3	108.9	13.0
2025	850.2	739.9	110.3	13.0
2026	860.2	748.4	111.8	13.0
2027	870.2	757.0	113.2	13.0
2028	880.2	765.5	114.7	13.0
2029	890.2	774.1	116.1	13.0
2030	900.2	782.6	117.6	13.1

Table 6 shows that the O&M costs as of 2030 are 802 billion KRW for PLC-only AMI and 745.6 billion KRW for hybrid AMI, indicating a 7% reduction of cost in hybrid AMI. The results in this subsection demonstrate that the installation cost is higher than the O&M cost. However, the cost reduction effect amounts to 117.6 billion KRW for installation cost, which is 61.2 billion KRW higher than that of O&M cost, suggesting a comparatively higher cost reduction effect. Figure 6 illustrates the comparison result of installation and O&M costs per deployment type.

Table 6. Comparison of O&M Cost Result per Deployment Method (Billion KRW).

Year	O&M Cost			
	PLC-Only	Hybrid	Reduction	
			Cost	Ratio (%)
2016	-	-	-	-
2017	7.3	6.7	0.6	8.2
2018	22.8	21.2	1.6	7.0
2019	47.5	44.2	3.3	6.9
2020	81.5	75.8	5.7	7.0
2021	124.5	115.8	8.7	7.0
2022	176.7	164.2	12.5	7.1
2023	240.7	223.8	16.9	7.0
2024	318.0	295.7	22.3	7.0
2025	396.3	368.4	27.9	7.0
2026	475.5	442.1	33.4	7.0
2027	555.7	516.6	39.1	7.0
2028	636.8	592.1	44.7	7.0
2029	718.9	668.4	50.5	7.0
2030	802.0	745.6	56.4	7.0

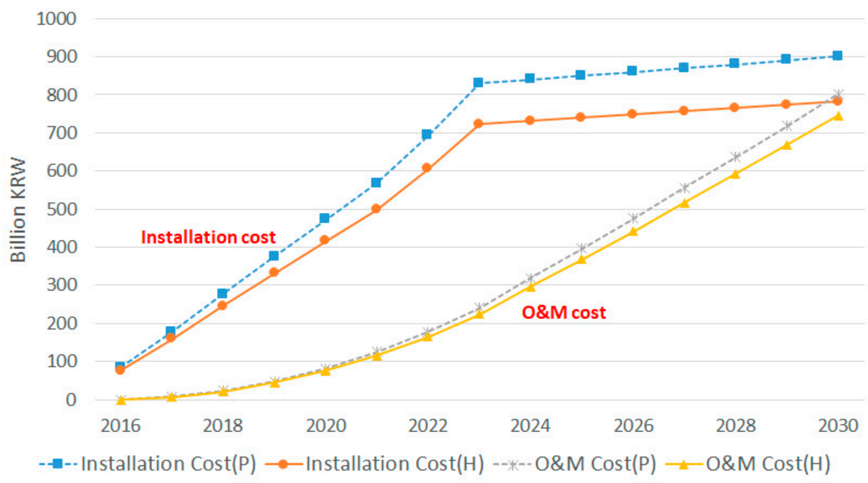

Figure 6. Comparison of Installation and O&M Cost Results per Deployment Method (P: PLC-Only, H: Hybrid).

3.2.3. Communications Network Cost

Examining cost by piece of equipment from the perspective of the communications network cost, it can be observed that the cost reduction effect of the DCU cost increased with the deployment of the hybrid AMI. The DCU cost for the PLC-only AMI was 885 billion KRW and the DCU + repeater cost for the hybrid AMI was 661.4 billion KRW, as presented in Table 7 and Figure 7. The analysis shows that as of 2030, the cost of the hybrid AMI decreased by 25.3% or 223.6 billion KRW in comparison to the PLC-only AMI. The DCU and repeater cost results for the hybrid AMI in Table 8 indicate that repeaters incur costs that are 6.7% of that incurred by DCUs.

Table 7. Comparison of DCU Cost Result per Deployment Method.

Year	DCU Deployment Cost			
	PLC-Only	Hybrid (DCU+RP)	Reduction	
			Cost	Ratio (%)
2016	58.1	43.5	14.6	25.1
2017	126.6	94.9	31.7	25.0
2018	203.0	152.2	50.8	25.0
2019	283.8	212.7	71.1	25.1
2020	365.1	273.6	91.5	25.1
2021	448.8	336.3	112.5	25.1
2022	558.0	418.0	140.0	25.1
2023	680.2	509.5	170.7	25.1
2024	708.7	530.6	178.1	25.1
2025	737.5	551.9	185.6	25.2
2026	766.4	573.4	193.0	25.2
2027	795.7	595.1	200.6	25.2
2028	825.2	617.0	208.2	25.2
2029	855.0	639.1	215.9	25.3
2030	885.0	661.4	223.6	25.3

The cost of a communications modem as of 2030 was estimated to be 817.1 for PLC-only AMI and 866.8 billion KRW for hybrid AMI. The hybrid AMI incurred costs that were higher by 49.7 billion KRW due to the influence of the unit price for wireless modems. This figure is equivalent to 6% of the DCU cost, which is a relatively small increase. Table 9 displays the communications modem cost results.

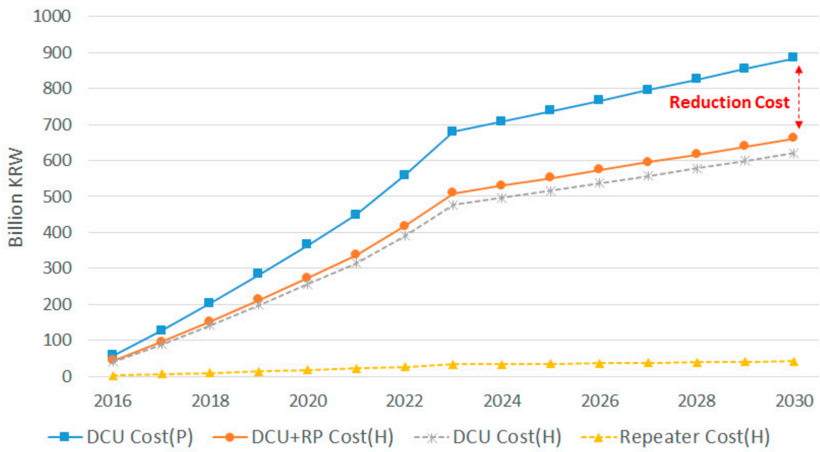

Figure 7. Comparison of DCU and Repeater Cost Results per Deployment Method (P: PLC-Only, H: Hybrid).

Table 8. Comparison of DCU and Repeater Cost Results for Hybrid AMI.

Year	DCU and Repeater Deployment Cost		
	DCU	**Repeater**	**Ratio (%)**
2016	40.6	2.9	7.1
2017	88.7	6.2	7.0
2018	142.3	9.9	7.0
2019	198.9	13.8	6.9
2020	255.9	17.7	6.9
2021	314.6	21.7	6.9
2022	391.1	26.9	6.9
2023	476.7	32.8	6.9
2024	496.7	33.9	6.8
2025	516.8	35.1	6.8
2026	537.1	36.3	6.8
2027	557.6	37.5	6.7
2028	578.3	38.7	6.7
2029	599.2	39.9	6.7
2030	620.2	41.2	6.6

Table 9. Comparison of Communications Modem Cost Results per Deployment Method.

Year	Communications Modem Deployment Cost			
	PLC-Only	**Hybrid**	**Reduction**	
			Cost	**Ratio (%)**
2016	26.2	32.7	−6.5	−24.8
2017	57.7	70.4	−12.7	−22.0
2018	95.6	114.1	−18.5	−19.4
2019	139.4	163.5	−24.1	−17.3
2020	188.4	217.6	−29.2	−15.4
2021	243.4	277.4	−34.0	−14.0
2022	311.5	351.7	−40.2	−12.9
2023	390.6	437.1	−46.5	−11.9
2024	449.5	496.4	−46.9	−10.4
2025	509.0	556.4	−47.4	−9.3
2026	569.2	617.1	−47.9	−8.4
2027	630.1	678.5	−48.4	−7.7
2028	691.8	740.5	−48.7	−7.0
2029	754.1	803.3	−49.2	−6.5
2030	817.1	866.8	−49.7	−6.1

3.2.4. Deployment Cost per Customer

Examining the AMI deployment cost from the perspective of cost per consumer, the analysis indicates there was a 5.9% cost reduction effect based on the total cost, including smart meters, with the PLC-only AMI decreasing by 135,000 KRW and the hybrid AMI by 127,000 KRW. Based on the cost of the communications network excluding smart meters, the cost per consumer for the hybrid AMI was calculated at 66,000 KRW, which translated into a 9.6% cost reduction effect compared to the 73,000 KRW of the PLC-only AMI. The analysis shows that the cost per consumer for the hybrid AMI was equal to 53% of the average overseas AMI installation cost. Examining the cost per consumer from the perspective of the installation and O&M costs for the communications network, the analysis indicates that the installation cost was 16.3% and the O&M cost was 8.6%, suggesting a big cost reduction effect for the installation cost. Table 10 and Figure 8 below show the cost per consumer by deployment method.

Table 10. Cost per Consumer by Deployment Method.

Division	Deployment Cost per Consumer (KRW)			
	Total	Communications		
		Total	Installation	O&M
PLC-Only	135,000	73,000	39,000	35,000
Hybrid	127,000	66,000	34,000	32,000
Reduction Ratio (%)	5.9	9.6	16.3	8.6

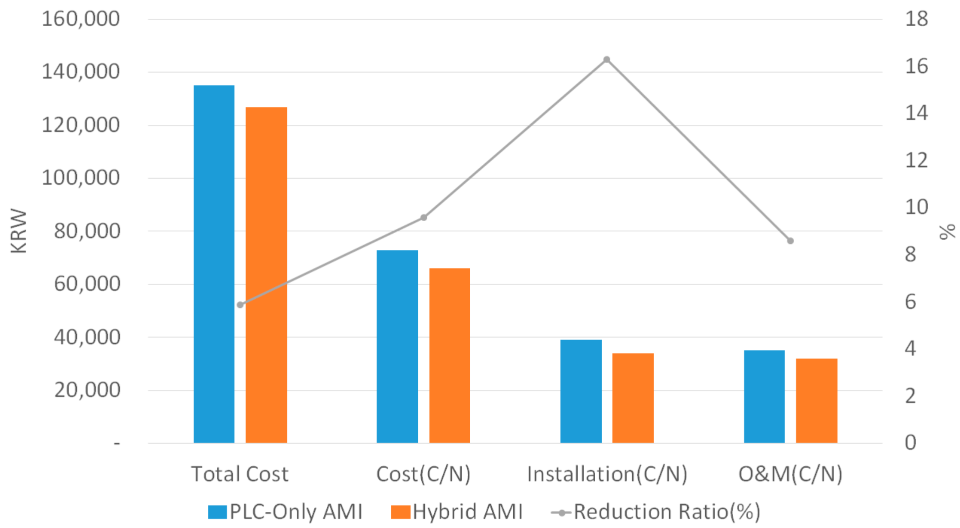

Figure 8. Cost per Consumer by Deployment Method.

3.2.5. Sensitivity Analysis for Hybrid AMI

A sensitivity analysis was performed to evaluate cost changes based on the PLC-only AMI deployment and the hybrid AMI deployment. The distribution of the modem quantity per DCU and the repeater quantity per DCU based on the configuration of the communications network was assumed a truncated normal distribution. In setting the limits to the truncated normal distribution, consideration was given to the fact that the maximum quantity accommodated by a smart meter per DCU for the PLC-only AMI was 200: therefore, the upper limit was set to 150 and the lower limit to 20 [40]. The upper limit of the number of smart meters per DCU for the hybrid AMI was set to 450 and the lower limit to 150, taking into account the target hybrid AMI deployment plan of 500 [39]. The upper and lower limits of repeaters were set to 1 and 7.5, respectively, by taking account of the average smart meter quantity accommodated per DCU in reference [36]. Table 11 presents the outcome of the sensitivity analysis setup based on the setup standard, a sensitivity analysis was performed using the Monte Carlo technique.

Table 11. Sensitivity Analysis Setup.

Scenario	Content	Configuration	
		Smart Meter per DCU	Repeater per DCU
PLC-Only	Lower Limit	20	-
	Upper Limit	150	-
Hybrid	Lower Limit	150	1
	Upper Limit	450	7.5

The results of the sensitivity analysis suggest that the hybrid AMI had a cost reduction effect in all sections, which can be seen in Figure 9. In the 5-percentile section, the PLC-only AMI showed a cost reduction of 1647.4 billion KRW and the hybrid AMI a cost reduction of 1508.5 billion KRW; in the 95-percentile section, the cost reductions were 1863.6 billion KRW and 1553.8 billion KRW, respectively.

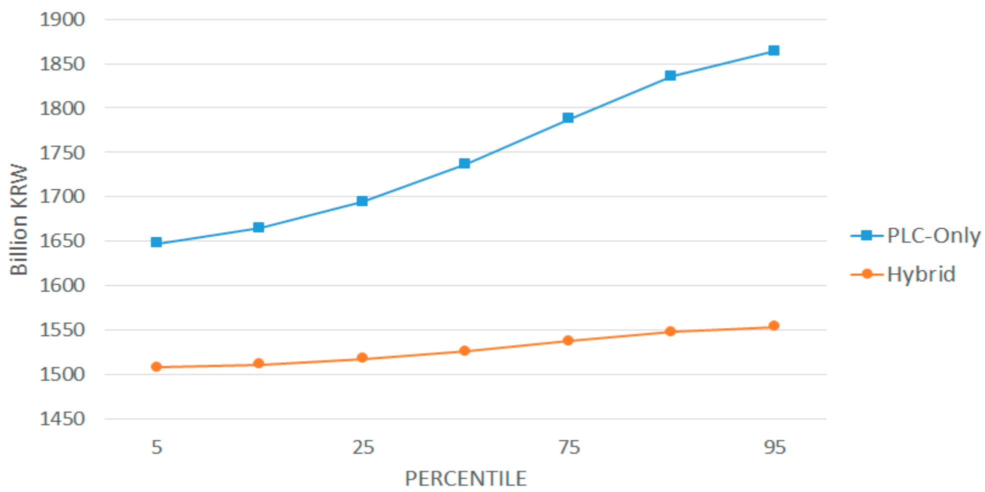

Figure 9. Sensitivity Analysis Result per Deployment Method.

By comparing the cost analysis results of the 95-percentile section, which was the largest cost distribution section for the hybrid AMI, and the 5-percentile section, the smallest cost distribution section for the PLC-only AMI, it became evident that the hybrid AMI had a low cost distribution of 93.6 billion KRW. Table 12 below and Figure 9 above reflect the results of the sensitivity analysis per deployment method.

Table 12. Sensitivity Analysis Result per Deployment Method.

Scenario	Percentile				
	5	25	50	75	95
PLC-Only	1647	1694	1737	1787	1864
Hybrid	1509	1518	1526	1538	1554

The results in this subsection demonstrate that based on the AMI deployment plan, the hybrid AMI can reduce the installation cost of a communications network by as much as 19.1% compared to the PLC-only AMI. On the other hand, the analysis of the 5-percentile section of both deployment methods indicates that the hybrid AMI has a minimum 8.4% cost reduction effect compared to the PLC-only AMI. It is evident from these results that the hybrid AMI is economically more effective than the PLC-only AMI

4. Conclusions

This study conducted a simulation based on the density of the installation environment and the configuration of the communications network to analyze the economic effects of installing a hybrid AMI communications network. It was assumed that a hybrid AMI was deployed in the overhead distribution line within a low-density region, and the results were compared and analyzed against the PLC-only method. Based on the total cost, including smart meters, the results of the cost analysis show that the hybrid AMI has a 5.6% or 174 billion KRW cost reduction effect compared to the PLC-only AMI. Based on the cost of the communications network, excluding smart meters, the results show that the hybrid AMI has a cost reduction of 173 billion KRW in comparison to the PLC-only AMI, which is equivalent to a 10.2% cost reduction effect. The total cost per consumer, including smart meters, for the hybrid AMI was 127,000 KRW, which is a 5.7% decrease compared to the PLC-only AMI. From the perspective of the communications network cost, the total cost per consumer, including smart meters, for the hybrid AMI was at 66,000 KRW, a 9.6% cost cut. The installation cost and O&M cost for the deployment of the hybrid AMI reduced by 13.1% and 7%, respectively, compared to the PLC-only AMI, and the reduced costs were significant. Examining the cost per piece of equipment from the perspective of the communications network cost, the analysis shows that the DCU cost had the highest reduction effect, dropping 25.3% following the deployment of the hybrid AMI. On the contrary, the cost of communications modems increased 6% due to the influence of the modem unit price. A sensitivity analysis of both deployment methods for communications network installation was performed, and the results indicated that the decline in the cost for the hybrid AMI in each section was as high as 19.1%, which was the maximum cost reduction effect. Based on these findings, it was evident that the hybrid AMI was economically effective in Korea. While this study applied the hybrid AMI in a non-downtown area, there would be more economic gain if the application were to expand into the downtown area. In addition, if a detailed system of area classification were used and quality of service for communications network configuration were applied, it would be possible to establish an effective configuration system for the communications network and to devise a deployment plan that takes account of reading cycles and regional characteristics. Although the cost analysis is performed for Korea AMI case in this work, the proposed approach is modeled with a system dynamics tool and can be easily applied to other cases by applying the specific scenarios and parameters. Future research will involve studying an optimal implementation plan for a hybrid AMI that configures an optimal communications network with minimum cost, taking account of the technical factors of building a communications network.

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Abbreviations

$AMID$	AMI deployment plan
CMC^{DP}	Communication modem deployment cost
CMC^{M}	Communication modem maintenance cost
CMP^{HW}	Communication modem hardware price
CMP^{InsT}	Communication modem installation price
CMP^{M}	Communication modem maintenance price
CMR^{Type}	Communication type rate
CMQ	Communication modem quantity
CS^{Cover}	Communication modem per smart meter
DCU^{Cover}	DCU per smart meter
$DCC^{O\&M}$	DCU operation and maintenance cost
$DCUC^{DP}$	DCU deployment cost
$DCUP^{HW}$	DCU hardware price
$DCUP^{InsT}$	DCU installation price
$DCUP^{M}$	DCU maintenance price
$DCUP^{O}$	DCU operation price
$DCUQ$	DCU quantity
g	Smart meter type coefficient
G	Smart meter type range
i	AMI deployment type (1 = Single, 2 = hybrid)
I	AMI deployment type range (I = 1 . . . 2)
j	Communication method type coefficient
J	Communication method range
OUR	Overhead and underground distribution line and rate
r	Installation area type coefficient
R	Installation area range
RPC^{DP}	Repeater deployment cost
RPC^{M}	Repeater maintenance cost
RPP^{HW}	Repeater hardware price
RPP^{InsT}	Repeater installation price
RPP^{M}	Repeater maintenance price
RPQ	Repeater quantity
RPR	DCU per repeater
$SMC^{H\&I}$	Smart meter deployment cost
SMP^{HW}	Smart meter hardware price
SMP^{InsT}	Smart meter installation price
SMQ	Smart meter quantity
SMR	Smart meter type rate
Y	Deployment year

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